Fermi-LAT Detection of Gamma-ray Pulsars above 10 GeV

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Abstract. The Large Area Telescope (LAT) on board the *Fermi* satellite has detected ∼120 pulsars above 100 MeV. While most γ-ray pulsars have spectra that are well modeled by a power law with an exponential cut-off at around a few GeV, some show significant pulsed high-energy (HE, >10 GeV) emission. I present a study of HE emission from LAT γ-ray pulsars and discuss prospects for the detection of pulsations at very high energies (VHE, >100 GeV) with ground-based instruments.

Keywords: Gamma rays – astronomical observations; Gamma-ray telescopes; Fermi LAT; Pulsars
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PULSARS ABOVE 10 GEV: THE EGRET VIEW (1991-2000)

Prior to the launch of *Fermi*, our best knowledge of the high-energy (HE, >10 GeV) γ-ray sky came from EGRET. Although *diffuse* emission accounted for the majority (∼1300) of the ∼1500 HE photons detected by EGRET in its 9 years in orbit, a few tens of such photons were coincident with five bright γ-ray pulsars: 10 from the Crab (7 in the peaks), 4 from Vela (all in the peaks), 10 from Geminga (5 in the peaks), 9 from B1706−44 (5 in the peaks), and 2 from B1951+32 (both in the peaks) [1].

FERMI-LAT CATALOGS: PAST AND PRESENT

Since its launch in 2008, the Large Area Telescope (LAT[2]) on *Fermi* has dramatically improved our knowledge of the γ-ray sky. The LAT has produced various catalogs in the last ∼3 years: the Bright Source List (0FGL) [3], using 3 months of data to describe 205 ($> 10\sigma$) γ-ray sources (30 pulsars). The First Pulsar Catalog (1PC) [4], based on 6 months of data, describing 46 γ-ray pulsars. The First/Second LAT Source Catalogs (1FGL[5], 2FGL[6]) using 11/24 months of data, and containing 1451/1873 sources (56/83 pulsars). Two catalogs, using 36 months of data, are currently in preparation: The *Fermi*-LAT Catalog of Sources above 10 GeV (1FHL[7]) describes the ∼500 "Hard" sources detected by the LAT (25 coincident with pulsars) while the Second LAT Pulsar Catalog (2PC) describes in depth the ∼120 LAT-detected (>100 MeV) γ-ray pulsars[8].

[1] `http://www-glast.stanford.edu/cgi-bin/people`

SEARCH FOR HE EMISSION FROM γ-RAY PULSARS

We used 3-year data sets as in 1FHL and 2PC. We first tried to determine how many of the 25 sources from 1FHL associated with LAT γ-ray pulsars show *significant* pulsations (and can therefore be *identified* as pulsars). These 25 sources include: 5 EGRET pulsars, 7 young (non-recycled) radio-selected γ-ray pulsars, 10 young (non-recycled) γ-selected pulsars, and 3 millisecond γ-ray pulsars.

Using the timing models from 2PC and `gtsrcprob`, we generated low energy (0.3–10 GeV) normalized[2] weighted light curves (*templates*). HE histograms were obtained using unweighted Front (Back) events within 0.6° (1.2°) of the known pulsar position, corresponding to ∼r95% of the PSF. For each pulsar, we defined, *a priori*, an "off-pulse" region, using Bayesian Blocks [9] (See Figure 1, **Left**), and evaluated the statistical significance of the HE events coming from the "pulsed" region of the light curve.

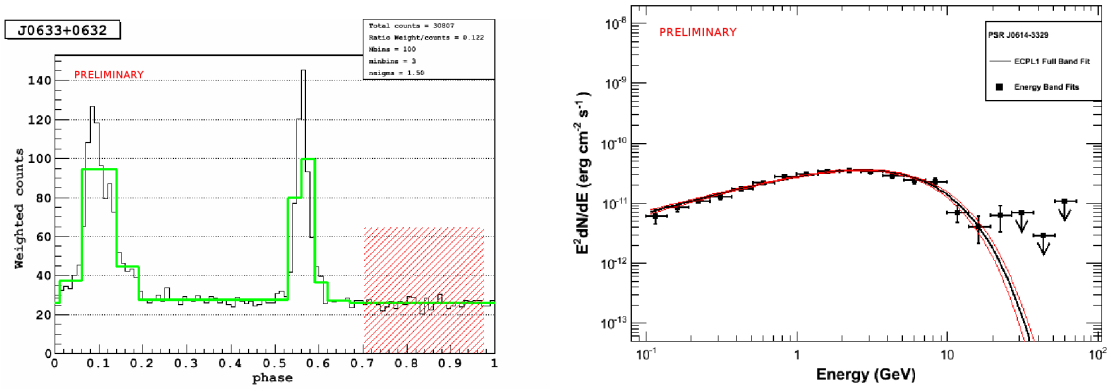

FIGURE 1. **Left** Preliminary off-pulse definition for PSR J0633+0633 using Bayesian Blocks [9]. **Right** Preliminary SED of PSR J0614-3329, showing possible evidence for >10 GeV emission.

We also selected a subset of the 117 γ-ray pulsars from 2PC which, based on their spectral energy distribution (SED, See Figure 1, **Right**), appear to emit above 10 GeV but did *not* meet the criteria for inclusion in 1FHL. These spectrally-selected 2PC pulsars not in the 1FHL catalog are: J0633+0632, J1509–5850, J1747–2958, J1838–0537, J1954+2836, J2017+0603, J2021+4026, J2238+5903, J2302+4442.

Our preliminary analysis shows that $\gtrsim$10 pulsars with significant pulsed HE emission (including J0007+7303, Crab, J0614-3329, Geminga, Vela, J1028-5819, J1048-5832, J1709-4429, J1809-2332, J2021+3651, and J2032+4127). Several others require a more definitive analysis before a firm detection can be claimed. Figure 2 shows the example of Geminga, where HE pulsed emission is apparent, albeit with a very different pulse shape than what is seen at lower energies. Some of the brightest pulsars (e.g. Geminga, Vela) show pulsed >25 GeV emission (Figure 3), while at >50 GeV, the LAT starts running out of statistics, much like EGRET did at >10 GeV (Figure 4).

[2] The area under the curve equals unity. We use 100 bins, so each bin width is 0.01 units of phase.

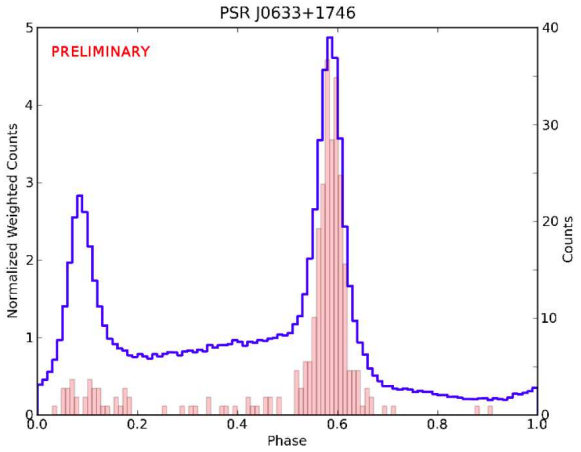

FIGURE 2. Normalized weighted light curve of Geminga in the 0.3–10 GeV energy range (blue, left scale) and unweighted HE light curve (pink, right scale). Weights based on 2PC spectral model.

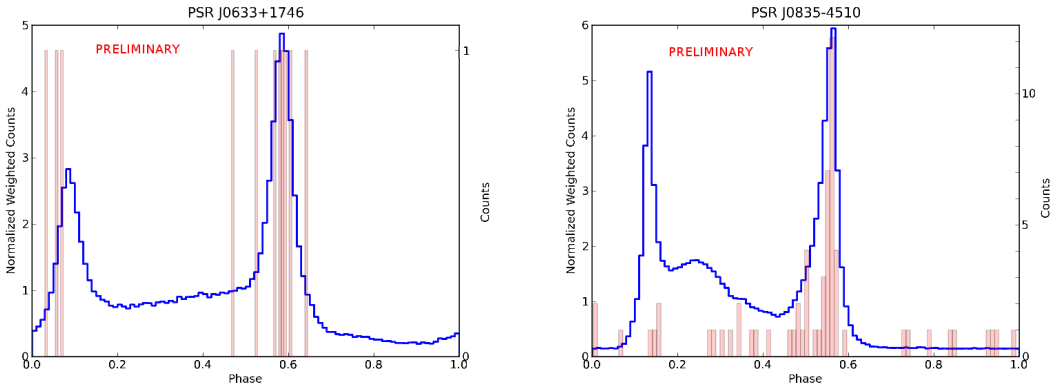

FIGURE 3. Blue curves (left scale), same as Figure 2: normalized 0.3–10 GeV weighted light curve. Pink (unweighted) histogram (right scale) of >25 GeV events: **Left** Geminga. **Right** Vela.

SUMMARY AND OUTLOOK

The LAT has dramatically increased our knowledge of the hitherto barely explored 10-100 GeV region of the γ-ray sky. A new LAT catalog in preparation (1FHL) will contain $\sim$500 HE sources, of which 25 are coincident with pulsars. In addition, the LAT has detected a large number of >100 MeV γ-ray pulsars (to be described in the upcoming 2PC), some of which show emission above 10 GeV. Future γ-ray pulsars may be discovered (e.g. in blind searches or radio searches of LAT sources), but these will necessarily be fainter than the brightest currently known. Top candidates for VHE pulsations depend on many assumptions and spectral extrapolations from 10 GeV upwards are notoriously unreliable. Thus, empirically speaking, the bright EGRET pulsars (e.g. Geminga, Vela) remain among the best candidates for VHE emission, while some of the newly-discovered bright LAT radio-quiet γ-ray pulsars (e.g. CTA1) are also very promising.

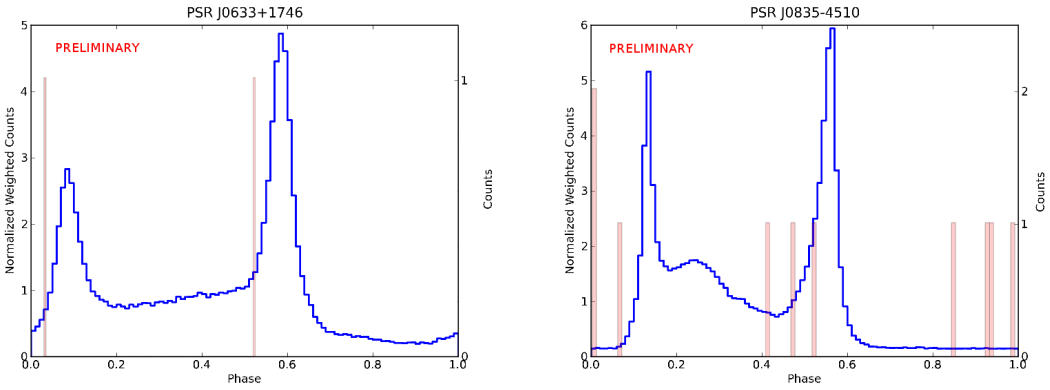

FIGURE 4. Blue curves, same as Figures 2 and 3. Pink (unweighted) histograms (right scale) show >50 GeV events: **Left** Geminga: 2 events above 50 GeV (57 and 77 GeV). **Right** Vela: 10 events above 50 GeV (5 events >100 GeV).

This preliminary study used 3 years of data. More data are currently available and it is important to keep in mind that in the statistics-limited high-energy regime, LAT sensitivity improves faster (i.e. αt) than at lower energies, where backgrounds dominate. Future improvements in reconstruction (e.g. Pass 8) could yield significant increases in effective area at higher energies. Future TeV experiments (e.g. CTA, HAWC) will complement and extend LAT observations in this crucial energy window.

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